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Short - Abstract

A multidisciplinary Carnegie Mellon University (CMU) research team studied new high temperature magnetic materials. CMU studied existing bulk soft materials and on novel nanocrystalline magnets in parallel. A search for new hard and soft magnetic materials was conducted. Prototypes for bulk soft magnets were Fe-Co alloys. The effects of grain size, structural order, orientation, and texture were studied to maximize induction and permeability, and minimize hysteretic and eddy current losses at elevated temperatures. Investigation of nanocrystalline materials for soft magnetic applications proceeded on two fronts. The first was plasma synthesis of magnetic nanoparticles followed by the use of compaction techniques to form dense magnets. The second route involved nanocrystallization of amorphous precursors to produce exchange coupled magnetic nanocrystals. The first has led to synthesis of metallic nanoparticles, of new core shell structures and nanocrystalline ferrites. The second has led to the discovery of a new nanocrystalline soft magnetic material called HITPERM for which work is continuing for the use of these materials in power electronic applications. Co-containing 2:17, 1:12, and 3:29 - based permanent magnet materials were investigated as hard magnetic materials (to 400 °C). We investigated the fundamental properties of these alloy systems as well as processing protocols for engineering microstructures. Co-containing 3:29 phase magnets have extended the temperature range of these materials. Rapid solidification processing was used as a means to try to tailor microstructure.

Advanced Magnetic Materials for Aircraft Power Applications
MURI FINAL REPORT
Air Force Office of Scientific Research
March 4, 2003

Carnegie Mellon University
Final Report

MURI
HIGH TEMPERATURE MAGNETIC MATERIALS

Table of Contents

For detailed information about results of the CMU MURI Program visit our Web site at http://neon.mems.cmu.edu/muri/

Advanced Magnetic Materials for Aircraft Power Applications

Carnegie Mellon University MURI - Final Report

Abstract

A multidisciplinary team of Carnegie Mellon University (CMU) researchers with substantial support from industrial, national and DOD laboratory collaborators were assembled to develop new materials with improved magnetic and mechanical properties at high temperature. Our CMU group worked on the refinement of existing soft bulk materials while conducting research on novel nanocrystalline magnets in parallel. The team also studied existing and new high temperature permanent magnetic materials for use in aircraft engine applications. Extensive microstructural and magnetic characterization facilities at CMU were used to characterize materials. A vigorous search for new magnetic materials, both hard and soft was conducted. We employed a group of undergraduate and graduate students and post-doctoral associates in pursuing our research goals. In addition, we worked closely with experts from industry and national laboratories and coordinated with Wright Patterson Air Force Base (WPAFB) to improve existing and develop new high temperature magnetic materials for aircraft applications.

Prototypes for bulk soft magnetic materials were Fe-Co alloys where we studied the effects of grain size, structural order, orientation, and texture so as to maximize induction and permeability, and minimize hysteretic and eddy current losses in the 550 - 600 °C temperature range. We examined $LaCo_{13}$ and other novel magnetic nitrides (Fe-nitride) as potential high induction, high T_c materials. We had a vigorous effort in investigating nanocrystalline magnetic materials for soft magnetic applications. This proceeded on two fronts. The first was plasma synthesis of magnetic nanoparticles followed by the use of compaction techniques to form dense magnets. The second route involved nanocrystallization of amorphous precursors to produce exchange coupled magnetic nanocrystals. The first has led to synthesis of metallic nanoparticles, of new core shell structures and nanocrystalline ferrites. The second has led to the discovery of a new nanocrystalline soft magnetic material called HITPERM for which work is continuing for the use of these materials in power electronic applications.

For hard magnetic materials capable of operating up to 400 °C we investigated Co-containing 2:17, 1:12, and 3:29 - based permanent magnet materials. We investigated the fundamental properties of these alloy systems as well as processing protocals for engineering optimal microstructures for hard magnetic properties. Co-containing 3:29 phase magnets have extended the temperature range of these materials. Rapid solidification processing was used as a means to try to tailor microstructure and to harness anisotropy and translate it into coercivity.

A. Brief History

A multidisciplinary team of Carnegie Mellon University (CMU) researchers, listed below, with substantial support from industrial, national and DOD laboratory collaborators were assembled to develop new materials with improved magnetic and mechanical properties at high temperature. The Multidisciplinary University Research Award (MURI) was entitled Advanced Magnetic Materials for Aircraft Power Applications (F49620-96-1-0454), Michael E. McHenry, PI and was pursued through a no-cost extension until August, 2002. The CMU group worked on the refinement of existing soft bulk materials while conducting research on novel nanocrystalline magnets in parallel. They also studied existing and new high temperature permanent magnetic materials for use in aircraft engine applications.

The details of the research have been summarized in a series of MURI booklets provided at annual review meetings held jointly with the University of Delaware and other research groups working on ancillary problems. Appendix I list the agenda for the Final MURI Review held May 10, 2001. The research out put of the CMU MURI Program has been detailed in these review documents. The MURI program continued through September, 2002 under a no-cost extension during which time industrial technology transfer interactions were pursued with ABB Corporation and the Magnetics Division of Spang and Company. During this time additional MURI research was published and applications of materials developed in the MURI project explored. Appendix II contains an list of archival publications produced with MURI support or partial MURI support.

The CMU MURI invented a new class of nanocrystalline $(Fe_{1-x} Co_x)_{88}M_7B_4Cu$ (M = Nb, Zr, Hf) soft magnetic materials called HITPERM. The excellent soft magnetic properties and magnetization that persists to elevated temperatures (up to ~ 600 C) as well as large magnetic inductions make these materials potential candidates for aircraft power electronic applications. The goals of the MEA include operation of aircraft engines at elevated temperatures. The CMU-ABB collaboration provided capital for facilitating development of these exciting alloys at CMU.

CMU researchers also developed new 3:29 phase permanent magnet materials. The 3:29 phase was shown to have large Curie temperatures suggesting its promise as a high temperature permanent magnet material. In collaboration with IIT Madras, CMU developed 3:29 magnets $(Pr_3(Fe_{1-x}Co_x)_{27.5}Ti_{1.5}$ (x = 0, 0.1, 0.2, 0.3 and 0.4) with up to 40% Co substitution for Fe. These exhibited large increases in Curie temperatures as compared with the Fe only phase.

CMU researchers developed of methods to prepare highly monodisperse FeCo nanoparticles for compaction, using a solution chemistry approach in nonaqueous solvents. They were able to tune the particle size with this synthesis between 15 and 900 nm, though for the smallest particle sizes, the surfaces of the equiaxed particles were somewhat rougher. They found that while the particle size could be varied dramatically, the average grain size ranged between 15 and 40 nm. The large particles prepared were only composites of smaller ones.

The MURI efforts had many notable educational and training achievements. These included the development of multidisciplinary course called "Structure and Applications of Magnetic Materials". Graduate students fully or partially supported by the MURI program have continued in important roles in government, academia and industry. Of particular note among these students are:

Zafer Turgut	Researcher at Wright Patterson Air Force Base through UES Inc., 4401 Dayton-Xenia Rd. Dayton, OH 45432.
Matthew Willard	NRC Postdoctoral Associate; Naval Research Laboratory

John Henry Scott	Member of Technical Staff, NIST
Roberta Sutton	Faculty, Division of Materials. The University of Queensland.
Amy Hsiao	Faculty Union College, Schnectady, NY.
Krishna Chowdary	Instructor , Bucknell University.

Many undergraduate research projects were supported by the MURI program including senior projects. Of particular note in terms of the subsequent accomplishments of these students are:

Katy Gallagher	Ph.d Trinity College, Dublin; Applied Physics, now NRC Postdoctoral Associate; Naval Research Laboratory.
Colin A. Ashe	NSF graduate student fellowship Ph.d Program. MIT MSE.
Daniel Schmidt	Ph.d Program. Cornell MSE.
Frank Johnson	Ph.d Program. CMU MSE.
Mitra Taheri	Ph.d Program. CMU MSE.
Asumini Kasule	M.S. Stanford, MSE.
Joshua McKinley	Ph.d Program. University of Michigan, MSE.
Nathan Browand	Cambridge, Applied Mathematics.
Cindy Dennis	Oxford, Physics
Elise Selinger	Technical Specialist - Foundry Team; Stryker Howmedica Osteonics
Rebecca Berngartt	M. S. Program, Lincoln University; Canterbury, New Zealand

B. Senior Personnel

B.1. Investigators: Michael E. McHenry (PI), David E. Laughlin, Sara A. Majetich, Henry R. Piehler, Anthony Rollett, W. Edward Wallace, Meiqing Huang, Shaoyan Chu, Anit Giri

B.2. Consultant: Fred Rothwarf

C. Summary of Accomplishments for Research Performed during MURI No-cost Extension

Industrial technology transfer interactions were pursued with ABB Corporation and the Magnetics Division of Spang and Company.

CMU participated in a collaborative research program with ABB in the area of advanced magnetic materials for high temperature applications. This was a technology transfer effort to the Multidisciplinary University Research Award (MURI) entitled Advanced Magnetic Materials for Aircraft Power Applications (F49620-96-1-0454), Michael E. McHenry, PI and its no-cost extension until August, 2002. The focus of the work was on the development of new high temperature soft and hard magnetic materials. ABB-CMU collaborative research focused on scaling-up rapid solidification processing efforts to produce precursors to HITPERM soft magnets and 3:29 phase hard magnetic materials.

CMU researchers continued rapid solidification processing to produce amorphous precursors to 3:29 phase permanent magnet materials. Rapid solidification and high energy ball milling were used in attempts to tailor the microstructures of materials to improve coercivities, a key materials property of the hard magnets. Arc melt spinning equipment was used, in collaboration with the Univ. of Pittsburgh to produce 3:29 phase materials. While promising intrinsic magnetic properties were demonstrated for 3:29 phase magnets, efforts to develop a nanostructure yielding large coercivities were unsuccessful. For both rapid solidification

processing and ball milling a decomposition of the 3:29 phase was observed to yield significant amounts of an α-FeCo soft magnetic phase that it was concluded limits their coercivity.

CMU scaled-up production of HITPERM magnet production using rapid solidification processing equipment both for soft and hard magnetic materials. The CMU/ABB collaboration provided funds for post-doctoral support and graduate student support in process development using this equipment as well as properties assessment and microstructural characterization. Pressurized quartz crucible jet casting equipment was used for production of 0.25 inch amorphous precursors to HITPERM materials. Process development for wider ribbons, namely planar flow casting was attempted. Planar flow casting crucibles were designed and iterations of PFC trials were performed. Ribbons were wound into cores and AC losses were studied. During the CMU/ABB collaboration, HITPERM was been shown to have superior soft magnetic properties including permeabilities in excess of 1000, and losses less than that of Supermendur. In the collaboration we identified a property window ($\mu > 1000$, B > 1.7 T, f > 200 kHz, T up to 300 C), appropriate for DC/DC converter applications of interest to the Air Force.

The development of processing facilities for scale-up of amorphous and HITPERM alloys was also used in the industrial interactions with the Magnetics Division of Spang and Company (**Magnetics**). **Magnetics**, has interest in developing amorphous Fe-based alloys for use in tape cores, powder cores and stacked laminates. New work was initiated involving optimization of Fe-based metallic glass compositions on CMU s melt spinner, prior to installation of a production unit at **Magnetics**. These materials also hold considerable promise for magnetic power electronic devices.

CMU and **Magnetics** have entered into a TIA-Consortium and are currently partners in a Dual Use Science and Technology Program funded by Wright Patterson Air Force base. Because of reduced size and weight it is anticipated that amorphous and nanocrystalline alloys can be formed into magnetic components, including powder and tape wound cores that will operate to 100 KHz and above, with the potential to replace and outperform conventional ferrites in certain applications for aircraft DC/DC converter circuits. We anticipate operational temperatures > 300 C will be possible. With further research to increase resistivity in HITPERM precursor materials we expect that we may be able to extend their operational frequency to > 200 KHz. The ultimate goal of the DUST program is to develop magnetic materials to achieve high temperature operation to > 300 C. Our partner, **Magnetics**, has interest in developing amorphous Fe-based alloys for use in tape cores, powder cores and stacked laminates. Joint work includes optimizing Fe-based metallic glass compositions on our melt spinner, prior to installation of a production unit at **Magnetics**, understanding how to make nanocomposites by compaction, how to relate their properties to those of the constituent nanoparticles, how to optimize their magnetic properties.

Another highlight of work performed in the NCE to the MURI was the development of methods to prepare highly monodisperse FeCo nanoparticles for compaction, using a solution chemistry approach in nonaqueous solvents. We were able to tune the particle size with this synthesis between 15 and 900 nm, though for the smallest particle sizes, the surfaces of the equiaxed particles were somewhat rougher. We found that while the particle size could be varied dramatically, the average grain size ranged between 15 and 40 nm. The large particles prepared were only composites of smaller ones. Several compaction methods were investigated for similar samples: cold and hot isostatic pressing, magnetic compaction, and plasma pressure compaction, where a conducting arc is struck through the sample and it is rapidly compressed. Cold isostatic compaction yielded only 60% of full density. Hot isostatic compaction was able to

generate fully dense samples, but this often occurred at the expense of significant grain growth, which was detrimental to the desired magnetic properties. The magnetic compaction technique is in principle ideal, since the compaction time is the shortest (45 microseconds). However, in its current form there are insufficient precautions taken to prevent sample oxidation, and the compaction pressure used was too low, yielding only 50% of full density. Our best results were obtained with the plasma pressure compaction method, with routine densities over 90% and often approaching 100%, particularly with milled materials. The company we collaborated with on this method was Materials Modification, Inc., of Fairfax, VA.

The AC magnetic properties of the composites were investigated in toroidal samples as a function of temperature. The highest permeabilities of the compacted FeCo samples were still fairly low, 100-200, but roll-off frequencies as high as 700,000 Hz were measured. Models of the temperature-dependent properties suggest that the magnetic coupling between grains is at least an order of magnitude lower than that within the grains, and this is the main target for improvement.

D. Conclusions and Recommendations

FeCo nanoparticles were compacted by a variety of methods reported on in the CMU thesis of Zafer Turgut. Since Zafer's thesis the MURI group pursued compaction of FeCo and ferrite particles in collaboration with IAP Research (Bhanu Celluri) using a magnetic compaction technique and with Teodor Veres of the Canadian NRC as well as the efforts described above. Again these techniques have yet to provide full densities. In soft magnetic materials, full density is imperative, and even in samples compacted to 99% of full density the residual porosity is enough to degrade the magnetic properties. While these techniques may be useful for nanocomposite permanent magnets, and low permeability ferrite materials, they have yet to provide the densities required for high permeability soft magnetic materials applications.

At this point in time the most attractive soft magnetic properties have been documented for the nanocomposite magnets produced by nanocrystallization of amorphous precursors. While these materials are brittle when fully nanocrystallized, they display improved ductility on partial nanocrystallization. There have also been reports of improved ductility in hot extruded nanocomposite materials. While a variety of soft magnetic nanocomposites have been produced, some with excellent soft magnetic properties, it is not felt that these materials are competitive with bulk FeCo laminates in terms of combined magnetic and mechanical properties. These materials do have promise in high temperature electronic inductive components that are of interest to the Air Force and are continuing to be pursued for these applications.

3:29 phase magnets studied by CMU researchers were determined to have promising intrinsic magnetic properties. Nanostructured 3:29 phase materials were produced by bll milling and rapid solidification. These nanostructures did not yielding large coercivities due to a decomposition reaction that yielded significant amounts of an α-FeCo soft magnetic phase that it was concluded limits their coercivity.

Appendix I: Final MURI Review Schedule – AFOSR 2001

MURI on Advanced Magnetic Materials
Final Program Review
May 10, 2001
AFOSR
801 N. Randolph St., 11th Floor Conference Room
Arlington, VA 22203-1977

0800-0830	Registration and Continental Breakfast
0830-0840	Opening Remarks – H. Weinstock, AFOSR
0840-0920	Exec. Summary: U. of Delaware, G. Hadjipanayis
0920-1000	Exec. Summary: Carnegie Mellon U., M. McHenry
1000-1020	Break
1020-1100	AFRL Perspective and Program, R. Fingers
1100-1130	U. of Nebraska Summary, D. Sellmyer
1130-1200	Virginia State U. Summary, A. Arrott
1200-1300	Lunch
1300-1400	U. of Delaware Annual Report (various speakers)
1400-1500	Carnegie Mellon Annual Report: **D. E. Laughlin - Moderator**
	Frank Johnson
	Amy Hsiao
	Suk-Joon Son
	Mei-qing Huang
	Krishna Chowdary
	Mitra Taheri
1500-1520	Break
1520-1540	U. of Nebraska (additional info), R. Skomski
1540-1600	DARPA Metamaterials Program, V. Browning

Discussion of DoD Magnetic Materials Programs and Future Requirements –
K. Hathaway, J. Prater, R. Fingers et al.

Appendix II: Publications Acknowledging MURI Support

• **Synthesis, Structure, and Properties of Carbon Encapsulated Metal Nanoparticles.** M. E. McHenry and S. Subramoney, Fullerenes:Chemistry, Physics and Technology, (K. M. Kadish and R. S. Ruoff, editors) John Wiley, (2000).

• **Amorphous and Nanocrystalline Materials for Applications as Soft Magnets.** M. E. McHenry, M. A. Willard and D. E. Laughlin, Progress in Materials Science, Vol. 44, 291-433 (1999).

• **Carbon Coated Nanoparticle Composites Synthesized in an RF PLasma Torch**. J. H. Scott, S. A. Majetich, Z. Turgut, M. E. McHenry, and M. Boulos, in Nanophase and Nanocomposite Materials II Symposium, ed. S. Komarneni, J. C. Parker, H. J. Wollenberger, Mater. Res. Soc., xii+567, pp. 219-224, (1997).

• **Structure and Magnetic Properties of SmCo7xZrx Alloys (x = 0 to 0.8).** M.Q.Huang, W.E.Wallace, M. E. McHenry, Q.Chen and B.M.Ma,: J. Appl. Phys. Vol. 83, pp. 6718-20, (1998).

• **Structure and Magnetic Properties of (Fe0.5Co0.5)88Zr7B4Cu1 Nanocrystalline Alloys.** M.A. Willard, D.E. Laughlin, M.E. McHenry, D. Thoma, K. Sickafus, J.O. Cross and V.G. Harris, Journal of Applied Physics, Vol. 84, 6773-6777, (1998).

• **Structural and Magnetic Properties of Pr3(Fe1-xCox)27.5Ti1.5 (x = 0.0, 0.1, 0.2, 0.3)** . V. R. Shah, G. Markandeyulu, K. V. S. Rama Rao, M. Q. Huang, S. Kuchimanchi and M. E. McHenry; J. Magn. Mag. Mats. 190, 233, (1998).

• **Distributed Magnetic Exchange Interactions and Mean Field Theory Description of Temperature Dependent Magnetization in Amorphous Fe88Zr7B4Cu1 Alloys.** K. A. Gallagher, M. A. Willard, D. E. Laughlin, and M. E. McHenry; J. Appl. Phys., Vol. 85, pp. 5130-32, (1999).

• **Effects of Co Substitution on the Magnetic Properties of Pr3(Fe1-xCox)27.5Ti1.5 (x = 0-0.3).** V. R. Shah, G. Markandeyulu, K. V. S.Rama Rao, M. Q. Huang, K. Sirisha , M. E. McHenry, J. Appl. Phys., Vol. 85, pp. 4678-80, (1999).

• **Magnetic Properties of HITPERM (Fe,Co)88CoxZr7B4Cu1 Magnets**. M.A. Willard, M.-Q. Huang, D.E. Laughlin, M.E. McHenry, J.O. Cross, V.G. Harris and C. Franchetti, Journal of Applied Physics Vol. 85, 4421-4423, (1999).

• **Structures and Magnetic Properties of RCo7-xZrx Alloys (R = Pr,Y or Er, x = 0-0.8).** M.Q. Huang, M. Drennan, W.E.Wallace, M..E. McHenry, Q.Chen and B.M.Ma, J. Appl. Phys., Vol. 85, pp. 5663-65, (1999).

• **Magnetic Properties and Microstructural Observations of Oxide Coated FeCo Nanocrystals Before and After Compaction.** Z. Turgut, N.T. Nuhfer, H.R. Piehler and M.E. McHenry; J. Appl. Phys., Vol. 85, pp. 4406-08, (1999).

• **Structural and Magnetic Phase Transitions in Ni-Mn-Ga Ferromagnetic Shape-memory Alloy Crystals.** S.Y. Chu, R. Gallagher, M. De Graef and M. E. McHenry; 2001 MMM-Intermag Conference in San Antonio, Texas, IEEE Trans Mag. Vol. 37, No. 4, 2666, (2001).

• **Structure and Thermomagnetic Properties of New FeCo-Based Nanocrystalline Ferromagnets.** F. Johnson, P. Hughes, R. Gallagher, D.E. Laughlin, M.E. McHenry, M.A. Willard and V.G. Harris, IEEE Transactions on Magnetics, Vol. 37, 2261-2263, (2001).

• **Mössbauer Measurements for a Nanocrystalline Fe44Co44Zr7B4Cu1 Alloy.** M. Kopcewicsz, A. Grabias, M.A. Willard, D.E. Laughlin and M.E. McHenry, IEEE Transactions on Magnetics, Vol. 37, 2226-2228, (2001).

• **Microstructural Characterization of (Fe0.5Co0.5)88Zr7B4Cu1 Nanocrystalline Alloys**. D. H. Ping, Y. Q. Wu, K. Hono, M. A. Willard, M. E. McHenry and D. E. Laughlin, Scripta Materialia, Vol. 45, 781-786, (2001).

• **Synthesis of Ferrite and Nickel Ferrite Nanoparticles using Radio-Frequency Thermal Plasma Torch.** S. Sön, M. Taheri, E. V. Carpenter, V. G. Harris and M. E. McHenry, Journal of Applied Physics 91(10), 7589-7591, (2002).

• **Anisotropy and First Order Magnetization Processes in (SmxPr1-x)3Fe27.5Ti1.5 (x = 0-1) and Pr3(Fe1-yCoy)27.5Ti1.5 (y = 0-0.4) Compounds**. G. Markandeyulu, V. R. Shah and K. V. S. Rama Rao, M. Q. Huang and M. E. McHenry; 2001 MMM-Intermag Conference in San Antonio, Texas, IEEE Transactions on Magnetics, Vol. 37, pp. 2615-2617, (2001).

• **Lorentz Microscopy Observations of a Nanocrystalline Fe44Co44Zr7B4Cu1 Alloy**. M. DeGraef, M.A. Willard, D.E. Laughlin and M.E. McHenry, IEEE Transactions on Magnetics, Vol. 37, 2343-2346, (2001).

• **Soft Magnetic Properties of Nanocrystalline Amorphous HITPERM Films and Multilayers**. M-Q. Huang, Y.-N. Hsu, M.E. McHenry and D.E. Laughlin, IEEE Transactions on Magnetics, Vol. 37, 2239-2241, (2001).

• **Magnetic Properties and Crystallization Kinetics of a Mn-Doped FINEMET Precursor Amorphous Alloy**. A. Hsiao, M. McHenry, D.E. Laughlin, M.R. Tamoria and V. Harris, IEEE Transactions on Magnetics, Vol. 37, 2236-2238, (2001).

• **Recent Advances in the Development of (Fe,Co)88M7B4Cu1 Magnets**. M.A. Willard, D.E. Laughlin and M.E. McHenry, Journal of Applied Physics, Vol. 87, 7091-7096, (2000).

• **The Effect of Field Cooling and Field Orientation on the Martensitic Phase Transformation in a Ni2MnGa Single Crystal**. S.-Y. Chu, A. Cramb, M. De Graef, D. Laughlin and M.E. McHenry, Journal of Applied Physics, Vol. 87, 5777-5779, (2000).

• **Magnetic Ordering: Some Structural Aspects** . D. E. Laughlin, M. A. Willard, and M. E. McHenry, *Phase Transformations and Evolution in Materials*, pages 121-137, edited by P.Turchi and A. Gonis, The Minerals, Metals and Materials Society, (2000).

• **Nano-Scale Materials Development for Future Magnetic Applications**. M. E. McHenry and D. E. Laughlin, Acta Materialia., Vol. 48, 223-238, (2000).

• **Magnetic Properties of HITPERM (Fe,Co)88CoxZr7B4Cu1 Magnets**. M.A. Willard, M.-Q. Huang, D.E. Laughlin, M.E. McHenry, J.O. Cross, V.G. Harris and C. Franchetti, Journal of Applied Physics Vol. 85, 4421-4423, (1999).

• **Thermal Plasma Synthesis Of g-FeNx Nanoparticles As Precursors For Fe16N2 Synthesis by Annealing.** Z. Turgut, D. E. Ferguson, M. Q. Huang, W. E. Wallace, M. E. McHenry. MRS Res. Symp. Proc. 577, (1999).

• **Magnetic Properties of HITPERM (Fe,Co)88CoxZr7B4Cu1 Nanocrystalline Magnets**. M.A. Willard, M. Gingras, M.J. Lee, V.G. Harris, D.E. Laughlin and M.E. McHenry, Proc. MRS Symp. Vol. 577, pp. 469-479, Materials Research Society, Warrendale, PA, (1999).

• **Recent Advances in 2:17 and 3:29 Permanent Magnet Materials** . K. V. S. Rama Rao, G. Markandeyulu, K. G. Suresh, V. R. Shah, U. V. Varadaraju, M. Venkatesan, M. Q. Huang, K. Sirisha, M. E. McHenry, V. G. Harris, Bull. Mater. Sci. 22, 509, (1999).

• **Magnetic Characteristics Of RCo7-XZrx Alloys (R=Sm,Gd,Pr,Er,Y and La)** . M.Q. Huang, W.E. Wallace, M.E. McHenry, S.G. Sankar, Q. Chen, and B.M. Ma, MRS Res. Symp. Proc. 577, 97, (1999).

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• **Study of Structural and Magnetic Properties and Exchange Interactions in (Y1-xGdx)3Fe27.5Ti1.5 (x = 0, 0.2, 0.5, 0.8, 1.0).** V. R. Shah, G. Markandeyulu, K. V. S. Rama Rao, M.Q.Huang and M. E. McHenry; Solid State Comm., Vol. 112, pp. 161-166, (1999).

• **The Effect of Mechanical Working on the In-Plane Magnetic Properties of Hiperco 50.** M. L. Storch, A. D. Rollett, and M. E. McHenry; J. Appl. Phys., Vol. 85, pp. 6040-42, (1999).

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• **Magnetic Coupling in Boron-Rich NeFeB Nanocomposites.** B. Lu, M.-Q. Huang, Q. Chen, B. M. Ma, and D. E. Laughlin; J. Appl. Phys. Vol. 85, pp. 5920-22, (1999).

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• **Time Dependent Properties of Iron Nanoparticles**, Keith D. Humfeld, Anit K. Giri, Sara A. Majetich, and Eugene L. Venturini, *IEEE Trans. Mag.* **37**, 2194 (2001).

• **AC Magnetic Properties of FeCo Nanocomposites**, Anit K. Giri, Krishna M. Chowdary, Keith D. Humfeld, and Sara A. Majetich, *IEEE Trans. Mag.* **36**, 3026-3029 (2000).

• **AC Magnetic Properties of Compacted FeCo Nanocomposites**, Anit K. Giri, Krishna M. Chowdary, and Sara A. Majetich, *Mater. Physics and Mechanics* **1**, 1-10 (2000).

• **Hard Magnetic Nanoparticles and Nanocomposites**, Anit Giri, Krishna Chowdary, and Sara A. Majetich, in *Advanced Hard and Soft Magnetic Materials*, eds. M. J. D. Coey, L. H. Lewis, B. M. Ma, T. Schrefl, L. Schultz, J. Fidler, V. G. Harris, R. Hasegawa, A. Inoue, and M. McHenry,*MRS Symp. Proc.* **577**, 197-208 (1999).

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